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SHEET TENSILE PROPERTIES OF TITANIUM ALLOYS AS AFFECTED BY TEXTURE

Technical Report by

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ABSTRACT

A study was carried out on the effect of specimen orientation on the sheet tensile properties of several titanium alloys. For these alloys, chemical analysis, microstructure, X-ray pole figures, and sheet tensile properties were determined at 10-degree increments from the rolling to the transverse direction. In addition to the conventional yield strength, tensile strength, and elongation values, strain gages were used to determine Young's modulus and Poisson's ratio. A study of plastic anisotropy was also made.

It is shown that several types of textures exist in these alloys and the characteristics of the mechanical properties are anisotropic and related to the texture type. A simple approximation of the anisotropic behavior patterns can be understood by relating these patterns to single-crystal properties.

CONTENTS

INTRODUCTION

There has been a growing interest in the possibility of employing the control of texture for the improvement of the strength of certain materials. The term "texture hardening", which was first employed by Backofen and his co-workers, certainly has this connotation, and the work in this field has that objective.[1-6] There are now several investigators attempting to utilize the suggestions of Hill[7] for structural improvements of components which are subjected to multiaxial stresses, particularly pressure vessels.[8] Although most of the interest for the structural use of anisotropic materials has been along these lines, this is not necessarily the only possibility, for it can be readily demonstrated that large variations in strength can occur even in uniaxial tension tests.[9] This large difference in uniaxial tensile strengths is particularly prevalent in certain hexagonal close-packed metals which have strong preferred orientations. There is no doubt that as more knowledge of these anisotropic plastic flow and fracture properties develop the industrial exploitation of these properties will grow.

Of the investigations carried on in this field, only relatively few have reported the textures of the material employed. Those which have determined textures have been somewhat limited in scope. Most of the prior work for titanium has been confined to commercially pure or the all-alpha type alloys, probably due to the fact that the alpha alloys seem to develop the textures in sheet material which are the most favorable for utilization of the texture hardening.

This is somewhat surprising for the all-alpha alloys are generally weaker and require considerable improvements by texture strengthening to be equivalent to a good heat-treatable alpha-beta alloy. Thus, it seems that the lack of information about textures, or the control thereof, in the alpha-beta alloys of titanium has inhibited this utilization in this field. This experimental investigation is the second part of a program for the study of the interrelationship of texture and tensile properties of titanium sheet materials. The first part was carried out on a commercially pure titanium.[10] This part is centered around the alloys of titanium.

TEST PROCEDURE

Chemical Analysis

The materials tested in this investigation were alloys of titanium, four sheets of Ti-6Al-4V, four sheets of Ti-16V-2.5Al, two sheets of Ti-8Mn (RC130A), two sheets of Ti-6Al-6V-2Sn, two sheets of Ti-4Al-3Mo-1V, and one sheet each of Ti-8Al-1Mo-1V and Ti-4Al-4Mn (RC130B). These sheets represent materials of both moderately old and fairly recent production. They also encompass a range of thicknesses from 0.022 to 0.130 inch. Chemical analysis was performed for the major alloying elements and the results are given in Table I.

Table I. CHEMICAL ANALYSIS

Alloy	Heat	Thickness (in.)	Element (weight percent) V	Al	Mn	Mo	Sn
6Al-4V	M2803	0.038	3.69	5.80			
	M2803	0.074	3.74	5.90			
	M7199	0.060	3.94	5.95			
	B22075	0.129	4.04	5.96			
16V-2.5Al	B22117	0.046	15.14	2.60			
	B24990	0.041	15.35	2.58			
	M23346	0.070	15.57	2.56			
	T22154	0.066	15.59	2.63			
RC130A	3442	0.062			8.64		
	A5221-16	0.122			7.95		
6Al-6V-2Sn	S	0.115	5.43	5.39			2.22
	H	0.115	5.06	5.56			2.40
4Al-3Mo-1V	X70006	0.060	1.05	3.64		2.86	
	M8773	0.022	0.97	3.33		2.99	
8Al-1Mo-1V	V1848	0.130	1.01	7.78		0.98	
RC-130B	B3263-B1	0.053		4.29		3.84	

Microstructure

The microstructures were determined and are shown in Figure 1 at 1000X magnification. The etchant utilized was 30 cc glycine, 10 cc nitric acid, and 10 cc hydrofluoric acid. The microstructure of three of the Ti-6Al-4V alloys (Figure 1a, b, and c) are equiaxed alpha with beta in the alpha grain boundaries indicative of as-received structure annealed in the alpha-beta field. The fourth heat of Ti-6Al-4V, B22075, is acicular alpha (transformed beta) with no evidence of retained beta or primary alpha (Figure 1d).

The metastable alpha-beta alloy Ti-16V-2.5Al structures are shown in Figures 1e through h. Heats B22117 (e) and M23346 (g) are in the as-received annealed or solution-treated condition, which is essentially the same; heat T22154 (h) is in the heat-treated condition. Heats T22154 (h) and B24990 (f) have a coarse grain which is an indication that these sheets were heated into the all-beta field.

The alpha-beta alloy Ti-8Mn (RC130A), heats 3442 (i) and A5221-16 (j) are in the as-received annealed condition with heat 3442 being somewhat larger in grain size. The structure is essentially alpha prime in a beta matrix.

Both heats of the alpha-beta alloy Ti-6Al-6V-2Sn are in the as-received condition (Figures 1k and 1). The structure is primarily an alpha matrix with retained beta outlining alpha grains.

Structures for the alpha-beta Ti-4Al-3Mo-1V are shown in Figures 1m and n. Heat X70006 structure is apparently indicative of an as-received annealed condition, retained beta in an alpha prime matrix. The microstructure for heat M8173 shows a solution-treated structure of a beta matrix with alpha prime.

The two remaining alpha-beta alloys, Ti-8Al-1Mo-1V and Ti-4Al-4Mn (RC130B), appear to be in the as-received mill-annealed condition (Figures 1o and p).

Texture

X-ray diffraction determination of the preferred orientation was carried out utilizing the reflection method described by Lopata and Kula[11] and the results are shown in Figure 2. Because of time and expense, only the pole figure for the basal plane was determined. In the cases where there was a large amount of beta, a pole figure for this phase was determined. Since most of the properties for hexagonal metals are symmetrical around the basal pole, it was felt that the basal pole figure would suffice.

The results shown in the figures confirm the general pattern as reported in the survey of Dillamore and Roberts.[12] One family of titanium textures, the alpha-deformation type, can be described as having a high intensity of basal poles in the sheet normal-transverse direction plane, and these poles are tilted at various angles toward the transverse directions. Because more work is needed, it cannot be definitely established that Figures 2a, b, c, g, h, i, j, m, and p are of this type. A characteristic of this type of texture is one which arises from the beta phase or appears in the alpha phase as a result of the transformation of beta to alpha on cooling through the transformation relationships of $(0001)_\alpha \parallel \{110\}_\beta$ and $\langle 11\bar{2}0\rangle_\alpha \parallel \langle 111\rangle_\beta$.

It has been found that the beta phase shows a (100) [011] type of texture[12] which is the type for the beta phase shown in Figure 2e and possibly 2f. The alpha textures are inherited from the beta (110) [011] type and are a result of the above transformation orientations as illustrated in Figures 2d, k, 1, m, and o.

This is only a brief description of the textures found and considerable more work is needed to completely describe the textures present. It seems that additional studies are needed, particularly on the alpha-beta alloys because of the complex nature of the working, which is done partly in the beta, partly in the alpha-beta, and finally in the alpha. Transformation occurs upon heating, annealing, or heat treatment, and the texture which develops as a result of all these events is imperfect.

Mechanical Testing

A series of sheet tensile specimens were machined at 10-degree increments from the rolling to the transverse direction. The specimen orientation is defined by the angle α that the specimen axis makes with the rolling direction as shown in Figure 3. In some cases, the specimens were cut for angles

Ti-6Al-4V

a. Heat 2803, 0.038" thick

b. Heat 2803, 0.075" thick

c. Heat M7199

d. Heat B22075

Ti-16V-2.5Al

e. Heat B22117

f. Heat B24990

g. Heat M23346

h. Heat T22'54

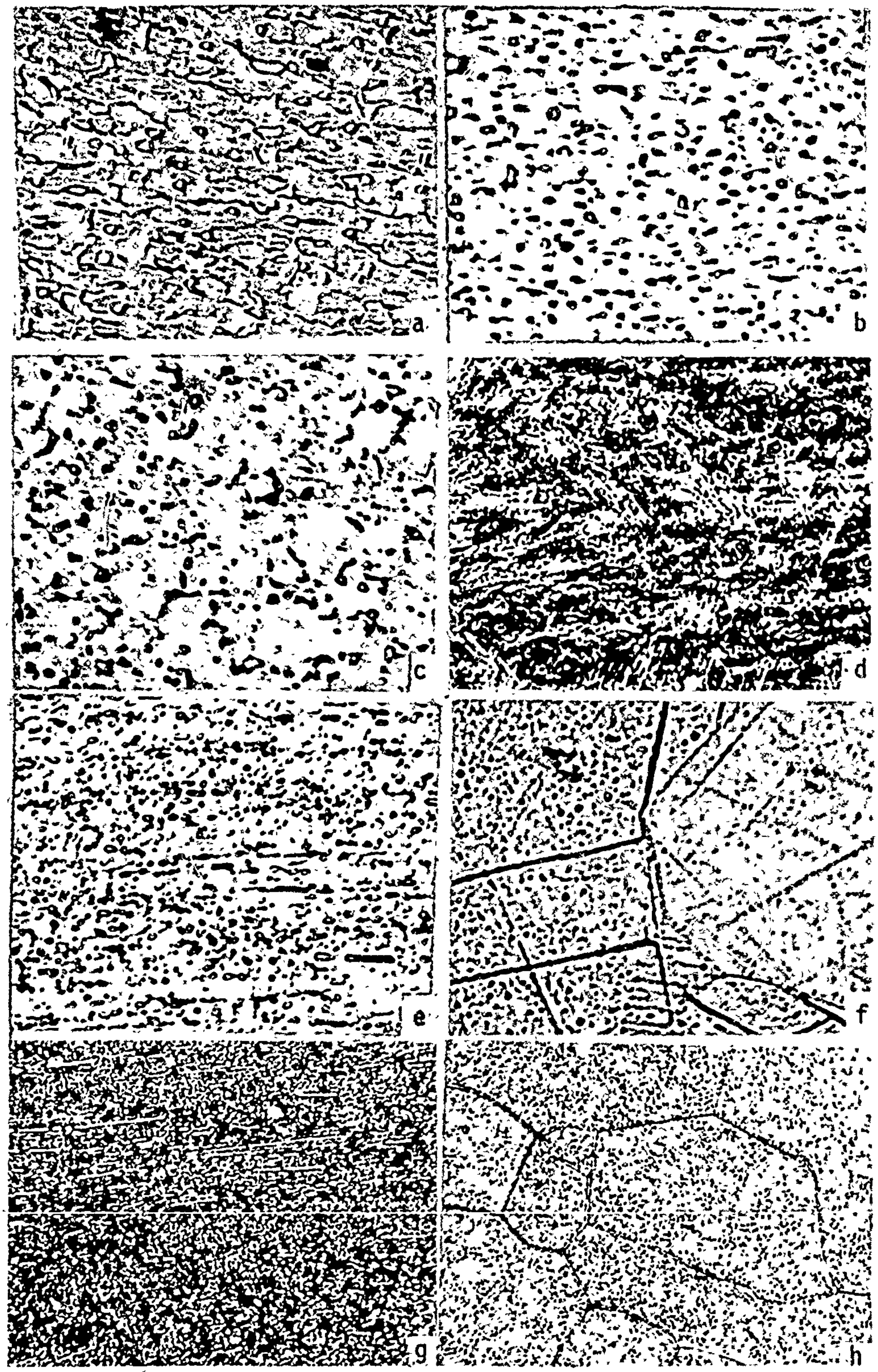
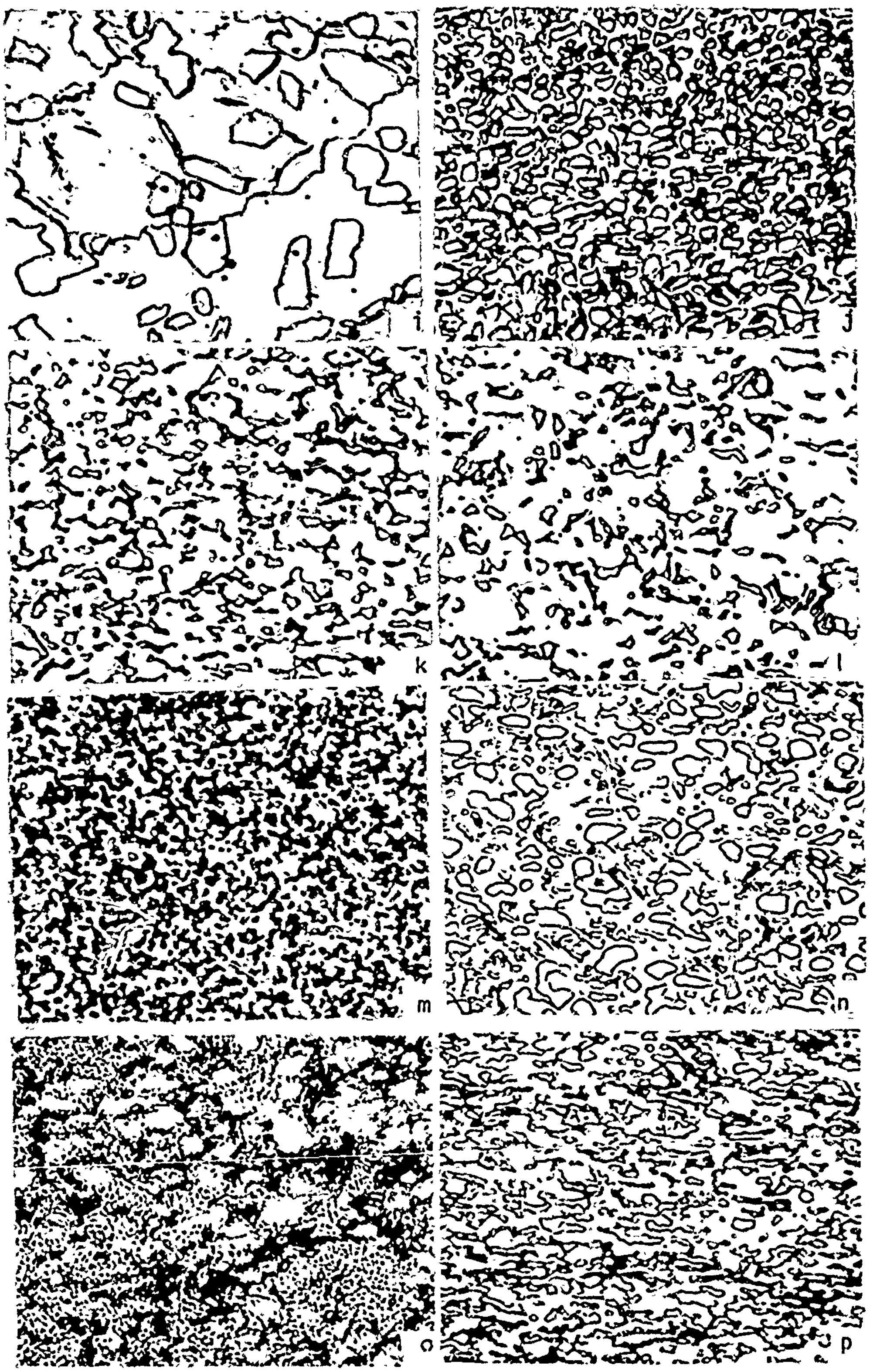


Figure 1a-h. MICROSTRUCTURES OF VARIOUS TITANIUM ALLOYS. Mag. 1000X



RC130A

i. Heat 3442

j. Heat A5221-16

Ti-6Al-6V-2Sn

k. Heat S

l. Heat H

Ti-4Al-3Mo-1V

m. Heat X70006

n. Heat M8173

o. Ti-8Al-1Mo-1V
Heat V1848

p. RC130B
Heat B3263-B1

Figure 1i-p. MICROSTRUCTURES OF VARIOUS TITANIUM ALLOYS. Mag. 1000X

Ti-6Al-4V

a. Heat M2803
0.033" thick

b. Heat M2803
0.070" thick

c. Heat M7199

d. Heat B22075

Ti-16V-2.5Al

e. Heat B22117

f. Heat 24990

g. Heat M23346

h. Heat T22154

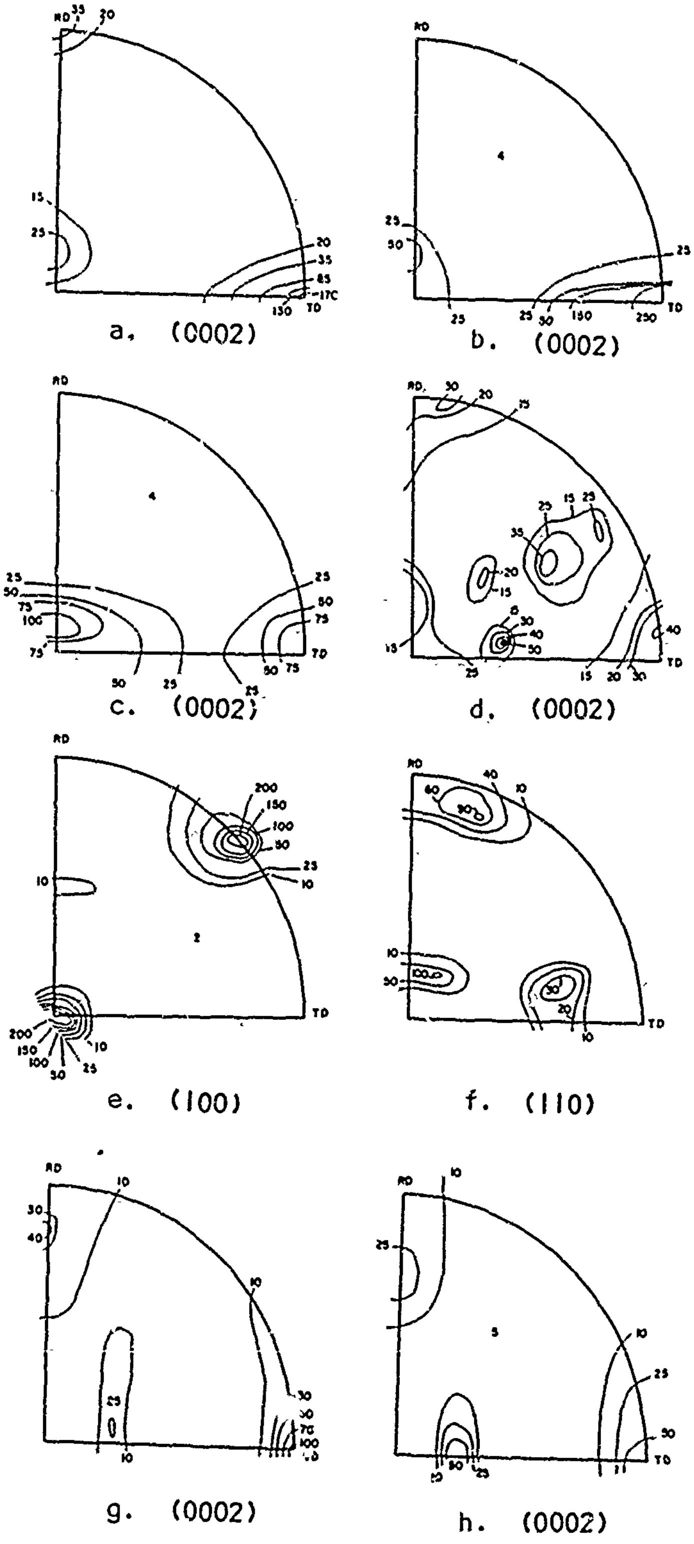
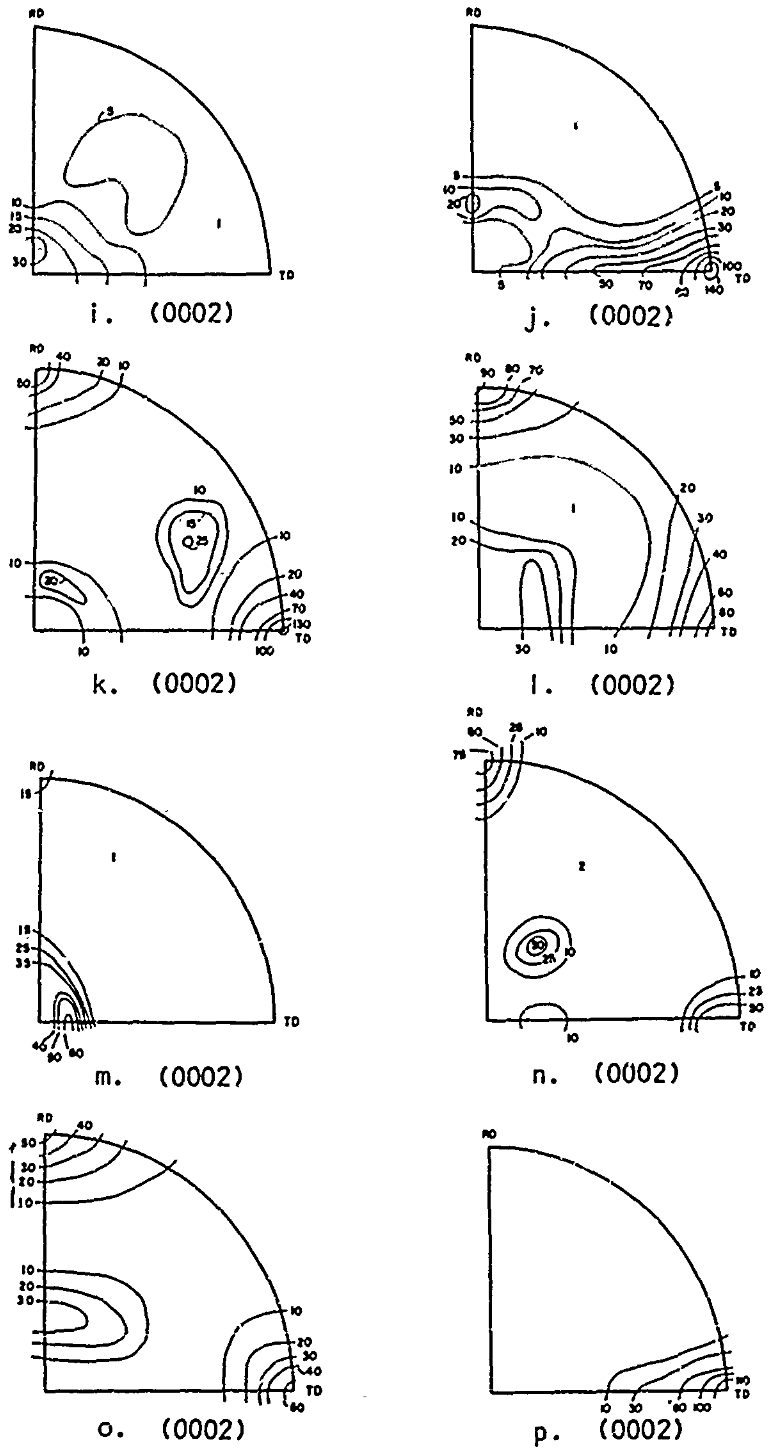


Figure 2a-h. POLE FIGURES OF VARIOUS TITANIUM ALLOYS



RC130A
i. Heat 3442
j. Heat 5221-16

Ti-6Al-6V-2Sn
k. Heat S
l. Heat H

Ti-4Al-3Mo-1V
m. Heat X70006
n. Heat M8173

o. Ti-8Al-1Mo-1V
Heat V1848

p. RC130B
Heat B3263-B1

Figure 2i-p. POLE FIGURES OF VARIOUS TITANIUM ALLOYS

up to 180 degrees. The longitudinal specimens would then be marked 0 or 180 degrees and the transverse 90 degrees.

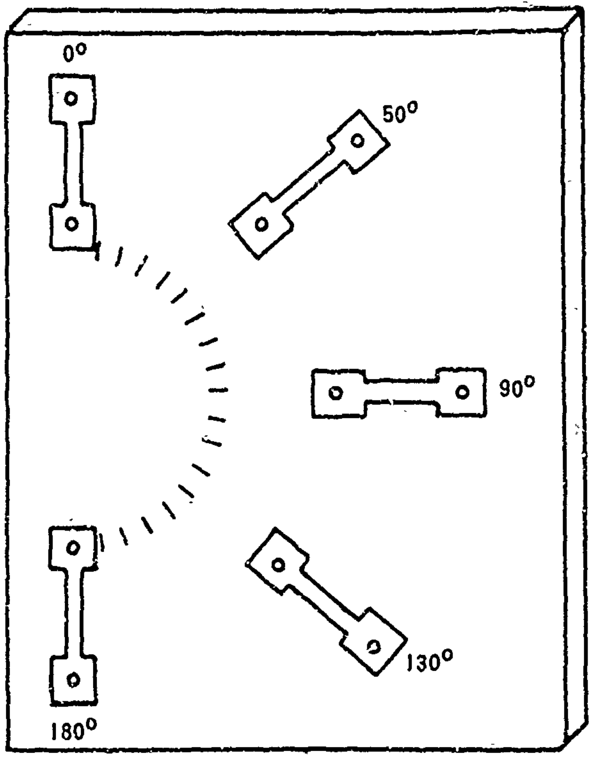


Figure 3. SCHEMATIC OF TENSILE SPECIMEN ORIENTATIONS

The test procedure and setup is essentially the same as that employed in previous investigations.[9,10] The geometry of the sheet tensile bar is shown in Figure 4.

In order to obtain precision strain measurements for the determination of Young's modulus and Poisson's ratio (both plastic and elastic), 90-degree, two-element, post yield rosette strain gages were utilized. The signal from the strain gages along with the load signal was fed into an X-Y-Y' recorder. This procedure produced two curves: a load versus longitudinal strain and a longitudinal strain versus transverse strain. These curves were used to determine the various special properties such as Young's modulus and Poisson's ratio. The conventional engineering tensile properties were obtained with a snap-on extensometer. All specimens were tested at room temperature on a 120,000-pound hydraulic universal testing machine at a strain rate of 0.005 inch per inch per minute. A schematic of the test setup is shown in Figure 5. More details on the method of determining various mechanical properties are available in a previous report.[9]

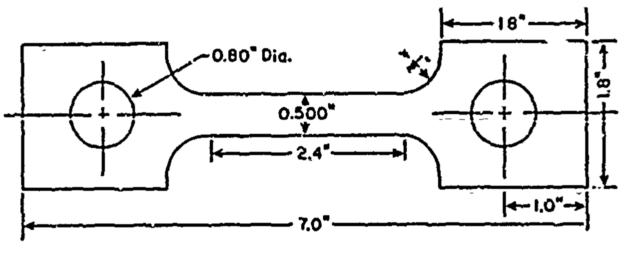


Figure 4. TEST SPECIMEN GEOMETRY

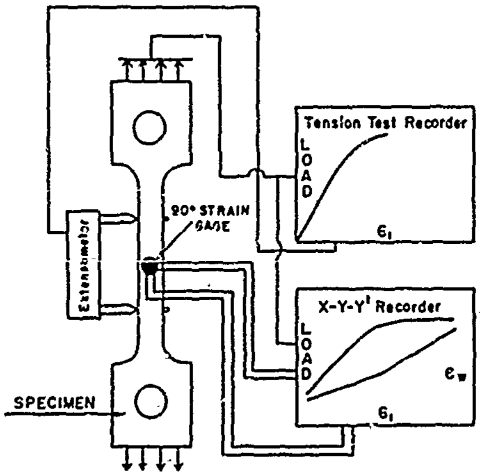


Figure 5. SCHEMATIC OF TESTING APPARATUS

DISCUSSION OF RESULTS

Young's Modulus

An understanding of the effect of texture upon Young's modulus is facilitated by a knowledge of single-crystal elastic properties. Much of this has been recently reviewed by Hearman.[13] Research has shown that for hexagonal single crystals, Young's modulus is sensitive to the angle that the applied stress makes with the basal pole and is symmetrical about this pole. Sonic measurements of Young's modulus in single crystals of titanium[14,15] have shown that Young's modulus is the lowest (14.5×10^6) when the stress axis lies in the basal plane and the highest (21.0×10^6) when the stress axis coincides with the basal pole. It can be seen that a variation of about 50 percent in modulus is observed in titanium single crystals. It would be expected that, for certain strange preferred orientations, a variation in Young's modulus will appear in polycrystalline titanium sheet. This discussion applies to the alpha or hexagonal phase but a similar one could be presented for the beta or body-centered cubic phase.

As can be seen from the above and from the three types of textures found in the alloys studied, it is to be expected that widely different behavior patterns will be evident. The experimental verification of this is illustrated in Figure 6. The variation of Young's modulus for the sheets with alpha-deformation type texture (6a, b, c, g, h, i, j, m, and p) shows a pattern which is similar to that observed in previous investigation.[10] Briefly, for these textures it was found that the lowest Young's modulus should appear in the rolling direction since the greatest number of grains would have the stress axis closest to the basal plane. If the texture is random or if the basal planes are parallel to the sheet surface, it would be expected that no variation in Young's modulus will occur with changing specimen orientation. On the other hand, if a strong texture exists, the variation in Young's modulus will depend upon how the basal poles are oriented. The sheet having the greatest tilt of the basal pole toward the transverse direction will have the greatest variation of Young's modulus in the transverse direction. Three very striking examples of this are shown in Figures 6a, b, and p. The presence of beta in the alpha matrix will have a tendency to modify this behavior pattern which results in raising Young's modulus in the rolling direction and lowering it around 30 to 40 degrees α.

Both of the other two types of textures produce similar patterns of Young's modulus as a function of specimen orientation. An extreme example is shown for the beta phase (body-centered cubic) in Figure 6e. Referring back to the pole figure (Figure 2-1), it can be seen that this is a very strong texture of the (100) $\langle 011 \rangle$ type. Thus, the high for Young's modulus in the rolling and transverse direction with a low at about 45 degrees is to be expected for body-centered cubic metals. The low in Young's modulus is usually found in the $\langle 100 \rangle$ direction with an intermediate value in the $\langle 110 \rangle$ direction and a high in the $\langle 111 \rangle$ direction. The alpha texture which develops from the transformation of this beta texture produces a similar pattern of Young's modulus with specimen orientation, primarily because the transformation relationships give rise to basal poles in the rolling direction. These

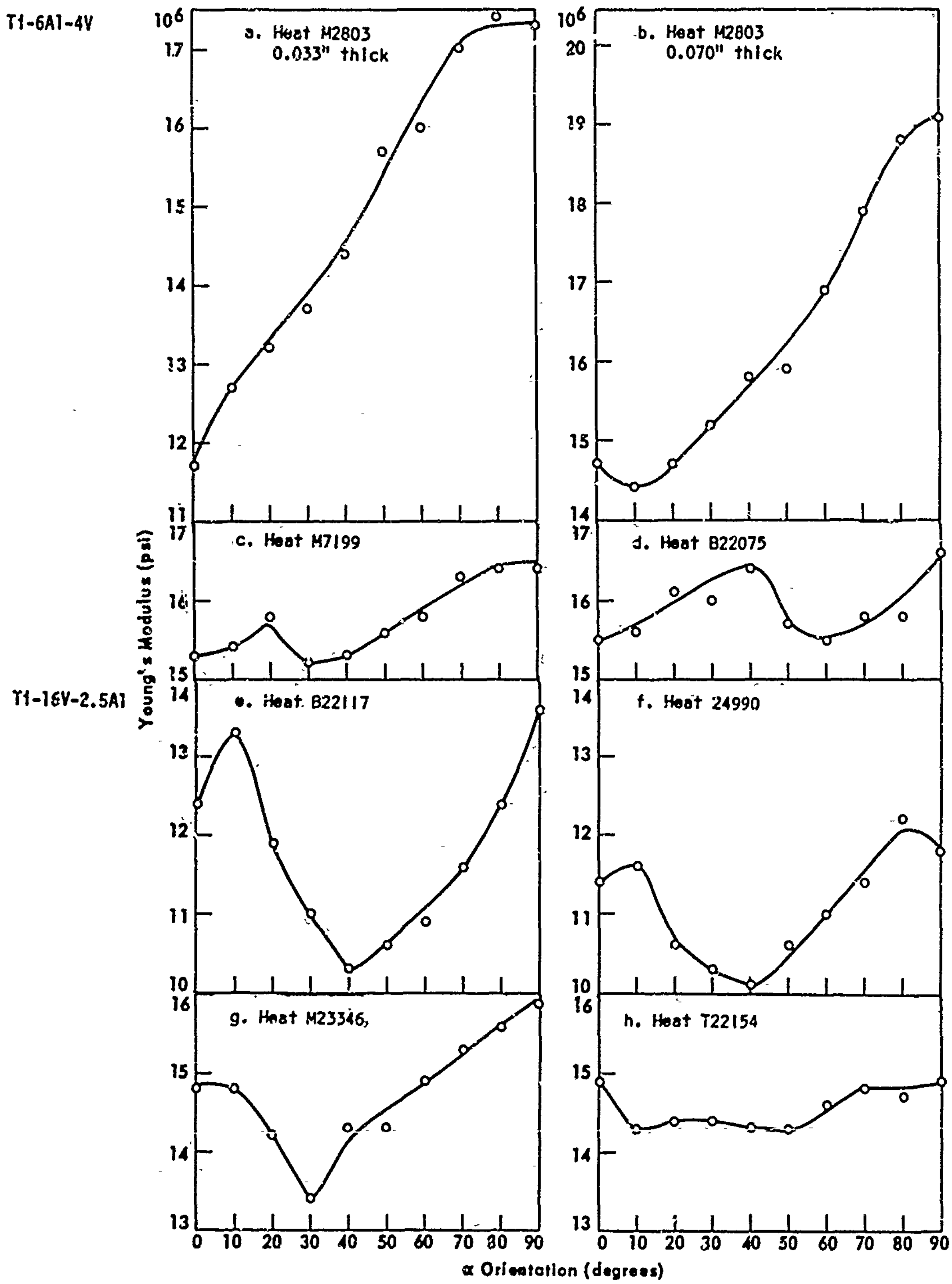


Figure 6a-h. VARIATION OF YOUNG'S MODULUS WITH SPECIMEN ORIENTATION (α)

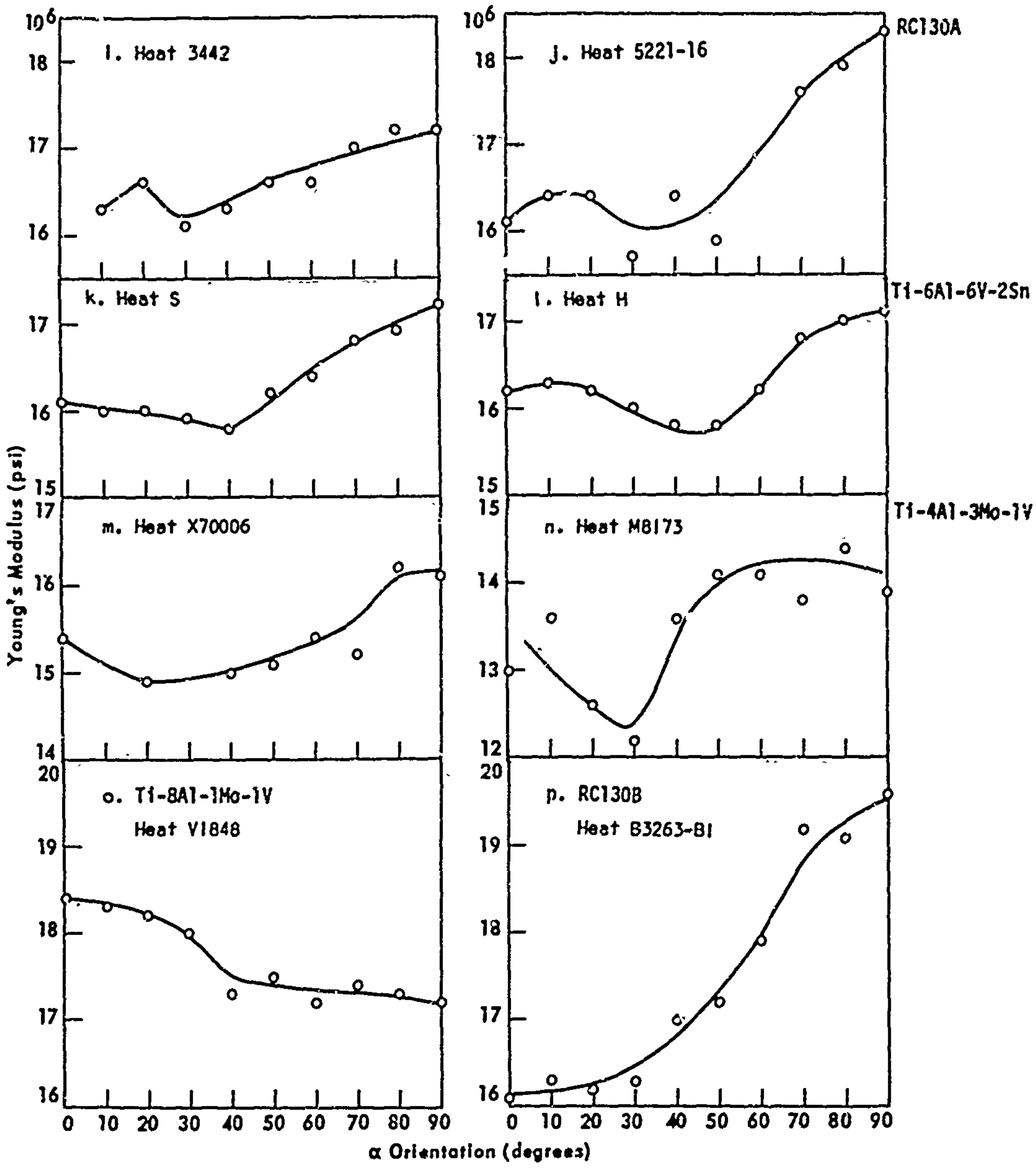


Figure 6i-p. VARIATION OF YOUNG'S MODULUS WITH SPECIMEN ORIENTATION (α)

basal poles in the rolling direction cause Young's modulus to be high as when α equals 0 degrees as shown in Figures 6k and l.

Poisson's Ratio

The transverse elastic contraction strain can also be shown to be anisotropic in single crystals.[13] Thus, the ratio of longitudinal extension to the

transverse contraction strain (Poisson's ratio) should be anisotropic. It has been previously shown[9] that in titanium and its alloys Poisson's ratio can vary from about 0.20 to 0.44. It is then to be expected that those sheets exhibiting strangely developed textures of certain orientations will have significant variations of Poisson's ratio. The results of this investigation are plotted in Figure 7.

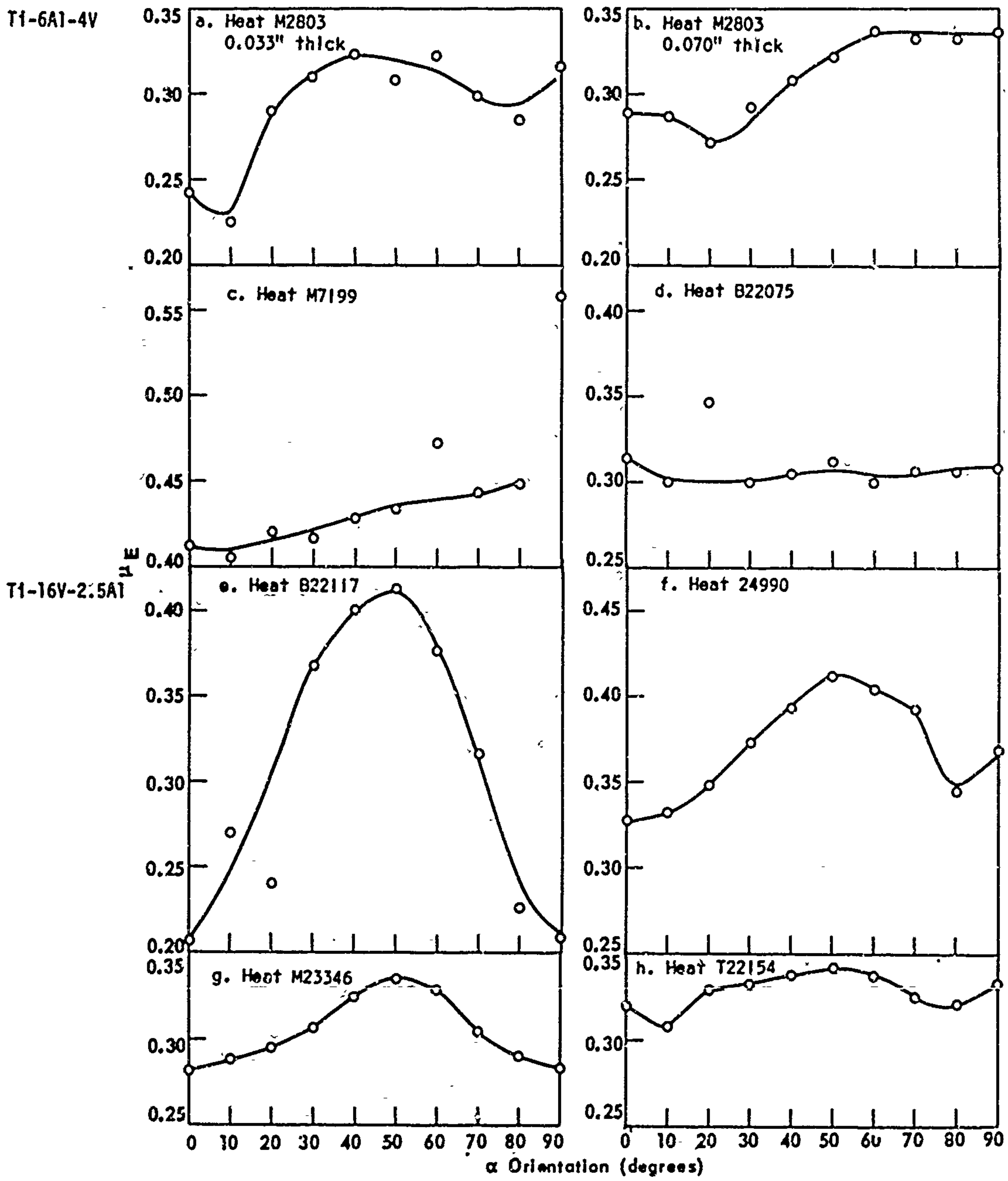


Figure 7a-h. VARIATION OF POISSON'S RATIO IN THE ELASTIC ZONE (μ_E) WITH SPECIMEN ORIENTATION (α)

If the curves are placed in the category of general texture type, certain behavior patterns evolve. For the alpha-deformation type texture, the variation of Poisson's ratio depends upon the tilt of the basal pole toward the transverse direction. When the basal poles are near the sheet normal, Poisson's ratio is high and does not vary to any large degree with specimen orientation as shown in Figure 7m. As the basal poles tilt toward the transverse direction, the value of Poisson's ratio decreases at all specimen orientations and to a larger degree near the rolling direction. Therefore, in this case, the lowest value of Poisson's ratio is found in the rolling direction as illustrated in Figure 7a.

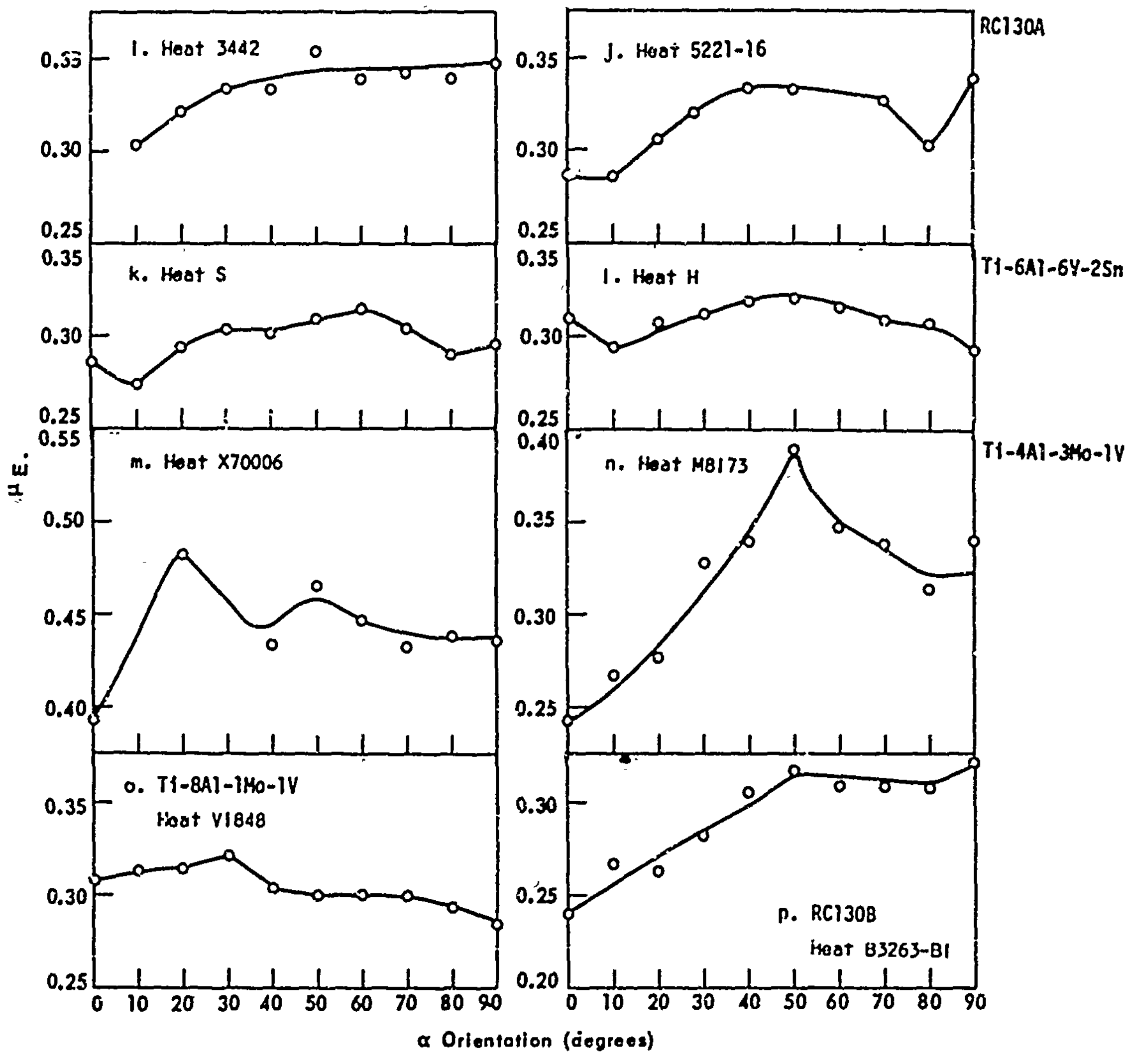


Figure 7i-p. VARIATION OF POISSON'S RATIO IN THE ELASTIC ZONE (μ_E) WITH SPECIMEN ORIENTATION (α)

The beta-phase texture and the alpha texture, which is a result of the transformation of the beta texture, have similar patterns of Poisson's ratio with specimen orientation. The curve in Figure 7e illustrates an extreme case of this. The value of Poisson's ratio is low in the rolling and transverse directions with a high at about 45 degrees.

Yield Strength

It is also demonstrated that the yield strength of single crystals is a function of orientation. It appears that the yield strength should also vary with specimen orientation depending upon texture type. For the alpha-deformation type, the variation will be small when the basal poles are near the sheet normal and large when they are near the transverse direction. An example of this large variation is shown in Figures 8a and p.

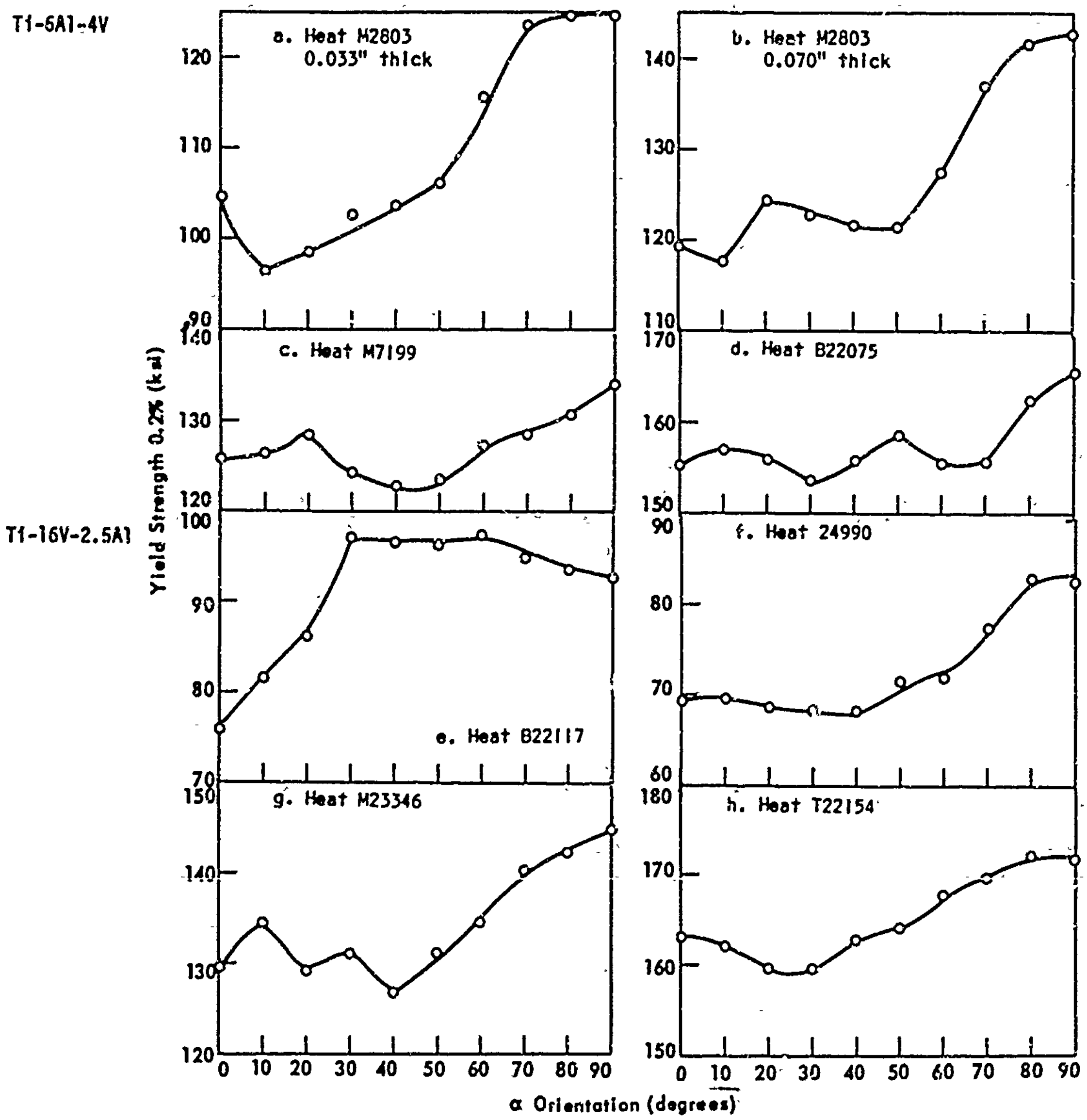


Figure 8a-h. VARIATION OF YIELD STRENGTH WITH SPECIMEN ORIENTATION (α)

For the other two texture types, the variation of yield strength with specimen orientation is small. In some cases, the value of yield strength is somewhat less in the region of specimen orientations around 45 degrees with high yield strength appearing in the rolling and transverse directions. Figures 8k and 1 illustrate this.

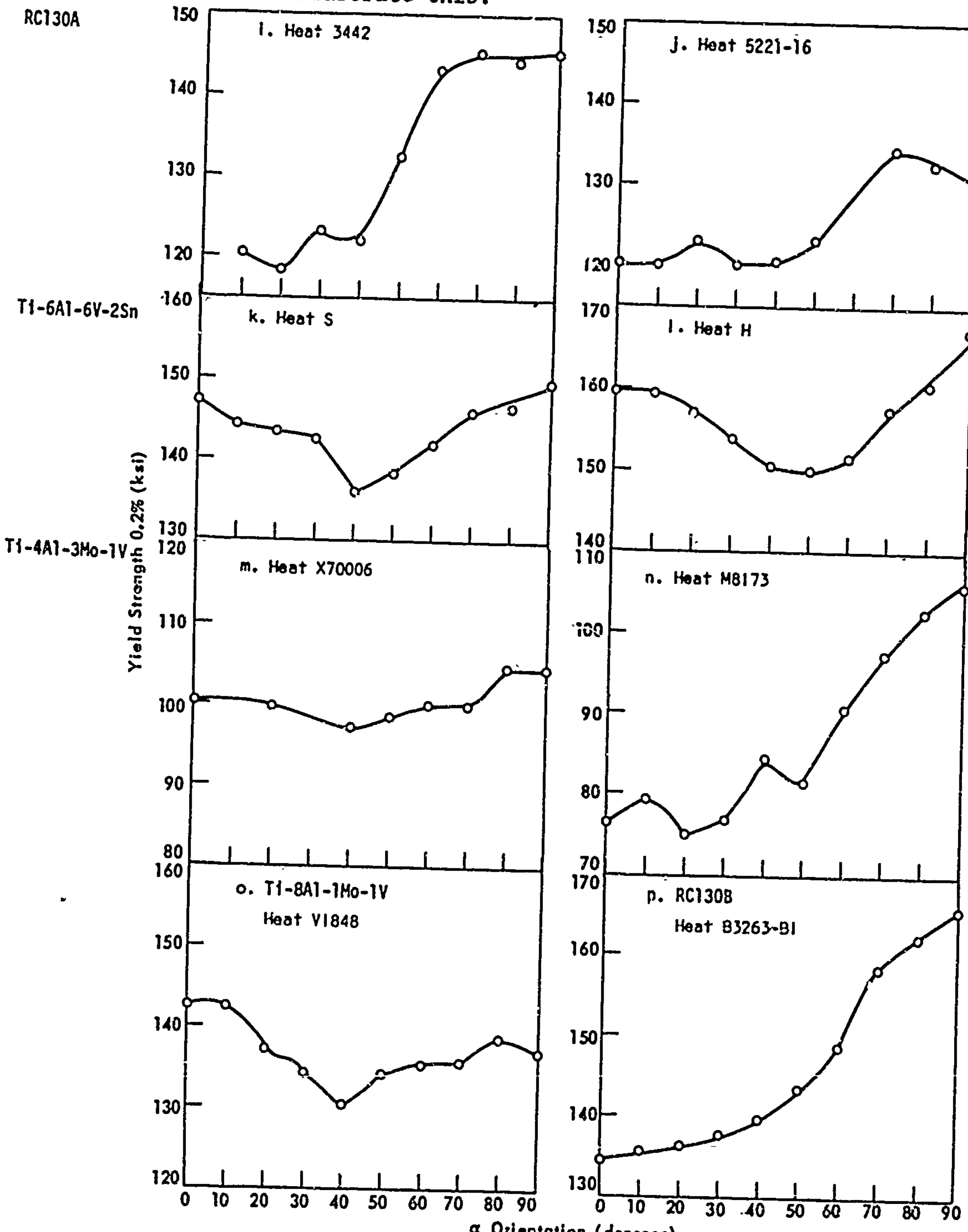


Figure 8i-p. VARIATION OF YIELD STRENGTH WITH SPECIMEN ORIENTATION (α)

Tensile Strength

The variation in tensile strength with specimen orientation depends upon two things, first, the yield strength, and second, the rate of strain hardening. Both of these properties can vary with specimen orientation in a complicated way so that a complicated pattern can easily develop as shown in Figure 9.

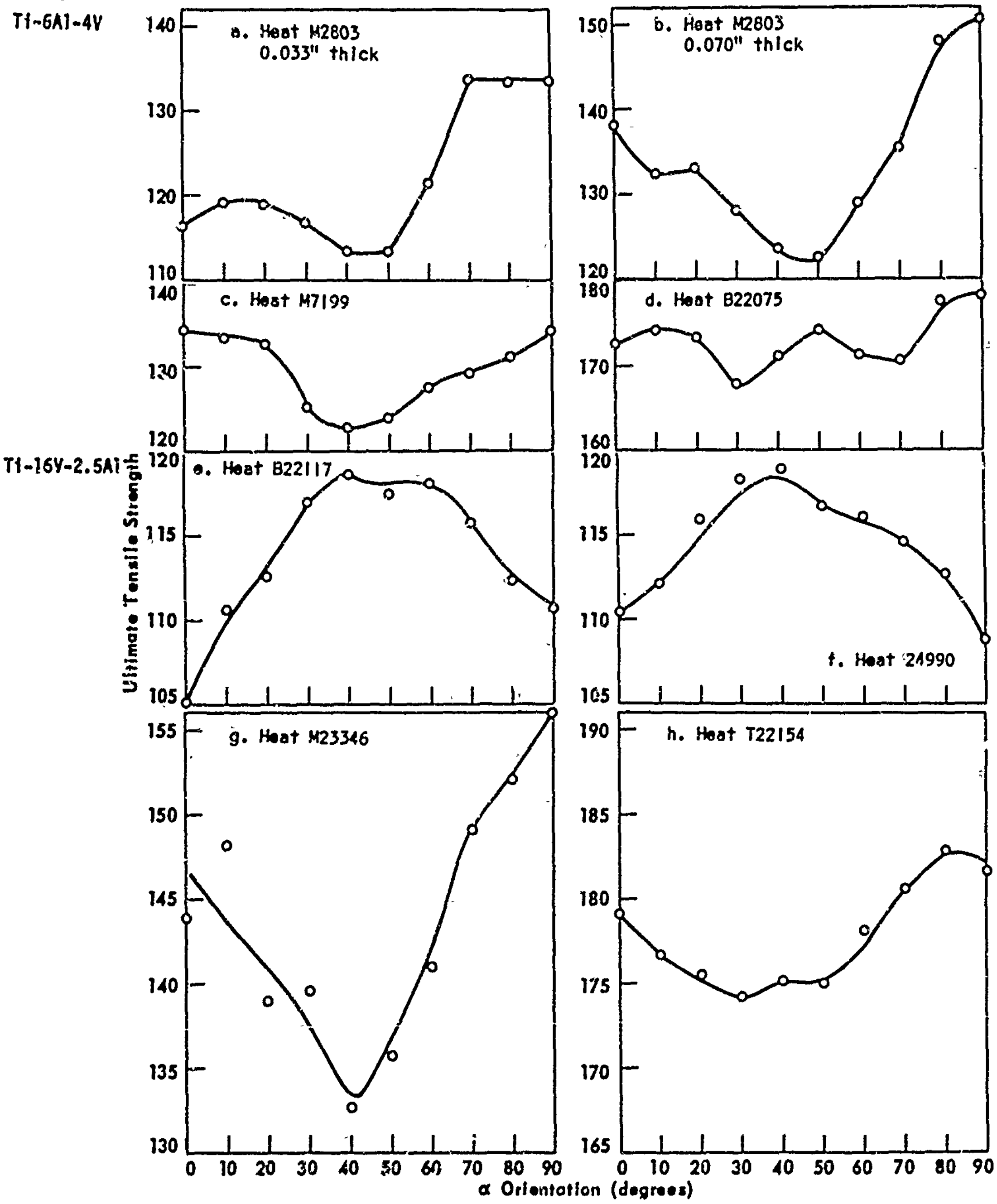


Figure 9a-h. VARIATION OF TENSILE STRENGTH WITH SPECIMEN ORIENTATION (α)

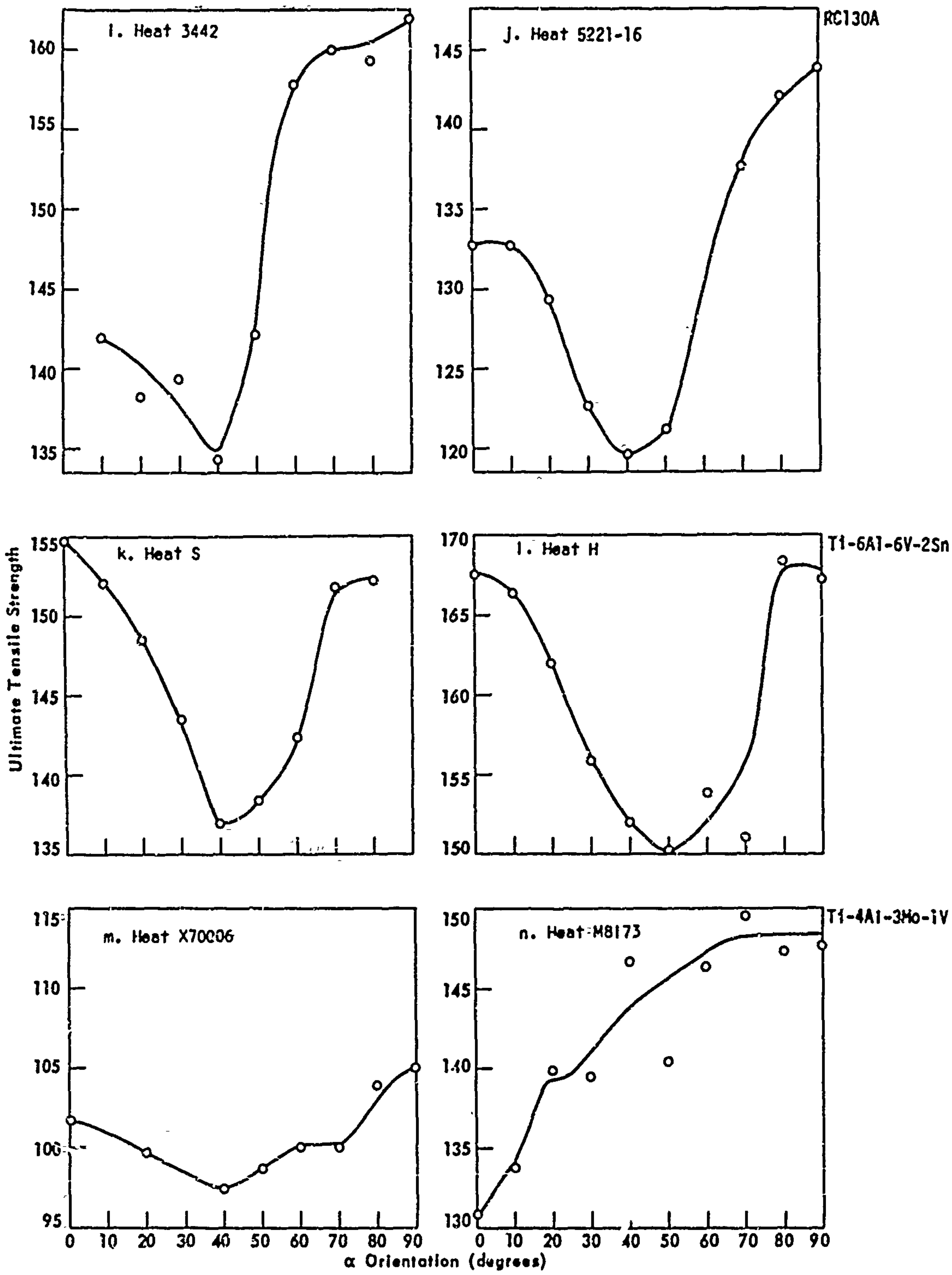


Figure 9i-n. VARIATION OF TENSILE STRENGTH WITH SPECIMEN ORIENTATION (α)

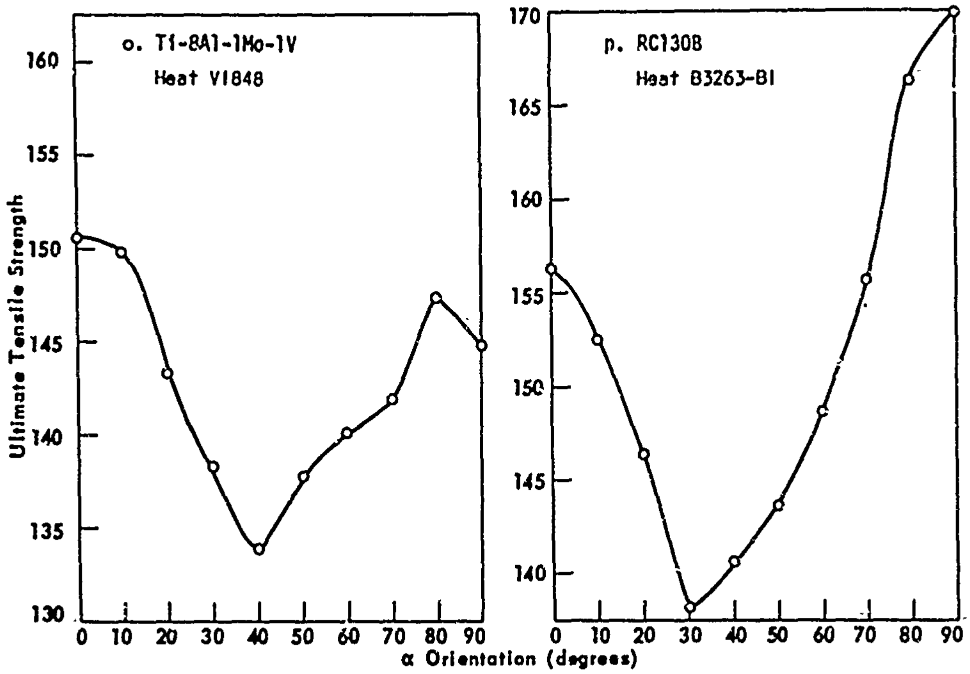


Figure 9o-p. VARIATION OF TENSILE STRENGTH WITH SPECIMEN ORIENTATION (α)

An analysis of these curves reveals that except for the case where the basal poles are near the sheet normal (Figures 9m and n), which we cannot explain, the curves follow two types; an alpha and a beta type. The alpha-phase type included both the alpha deformation texture and the alpha-tranformed-beta deformation type. The primary feature of these curves is a low tensile strength at specimen orientation around 40 to 50 degrees, a high in the rolling direction, and sometimes higher value in the transverse direction.

The beta-phase type (Figures 9e and f) shows a high at 40 to 50 degrees and a low in the rolling and transverse directions.

Plastic Poisson's Ratio

Of all the mechanical properties, the ratio of plastic strains is probably more sensitive to texture than the others studied. This is clearly evident from the large variations shown in Figure 10. As pointed out previously,[9] the values of Poisson's plastic strain ratios are related through constancy of volume to the more commonly used value of the ratio of lateral contraction strains which is called R. It is difficult to describe the pattern displayed by this data. It appears, however, that the lowest value is in the rolling direction and, as the specimen orientation moves to the transverse direction, the value increases to a maximum at 40 to 50 degrees and then decreases. The value for the transverse test, in general, is somewhat

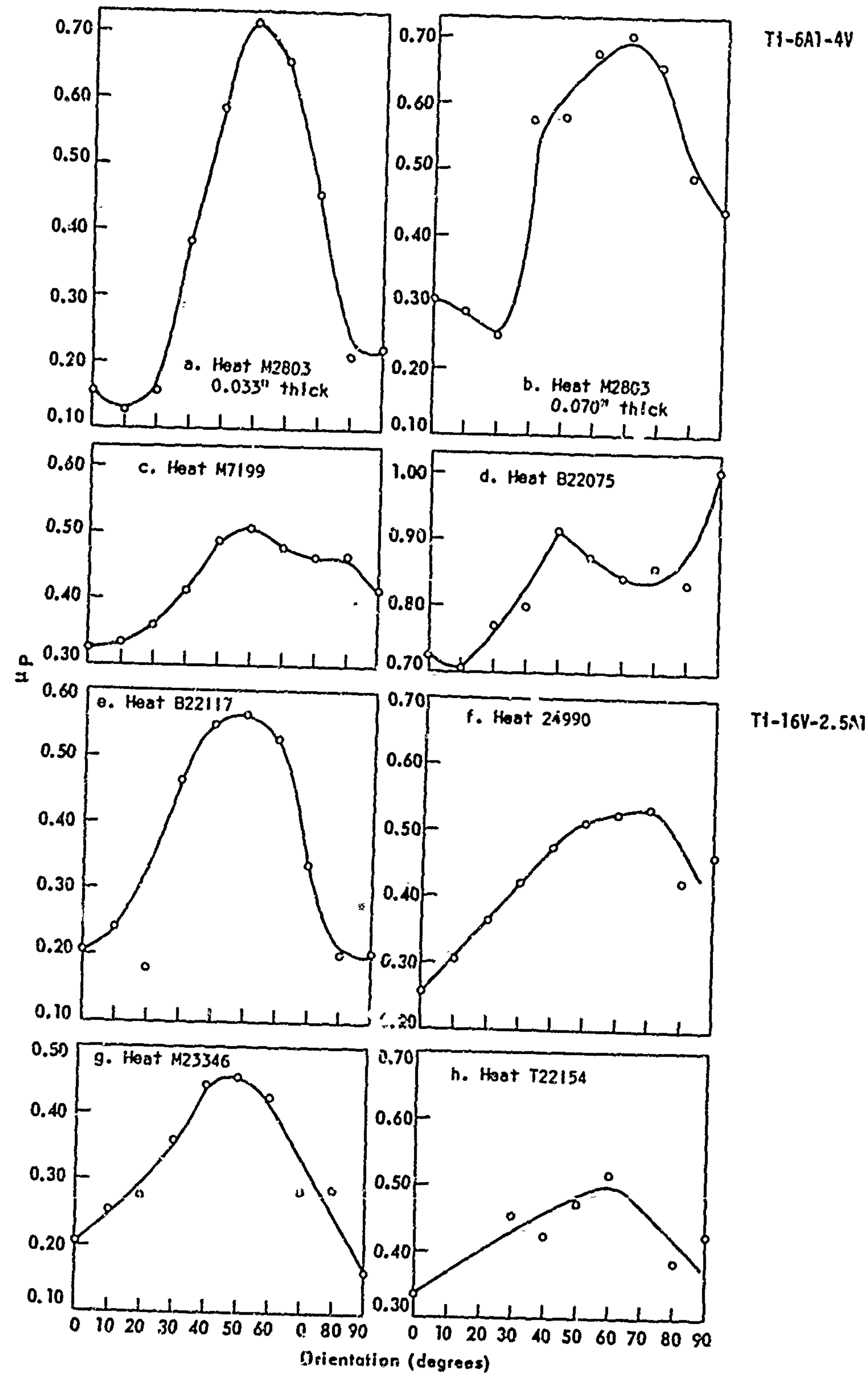


Figure 10a-h. VARIATION OF POISSON'S RATIO IN THE PLASTIC ZONE (μ_p) WITH SPECIMEN ORIENTATION (α)

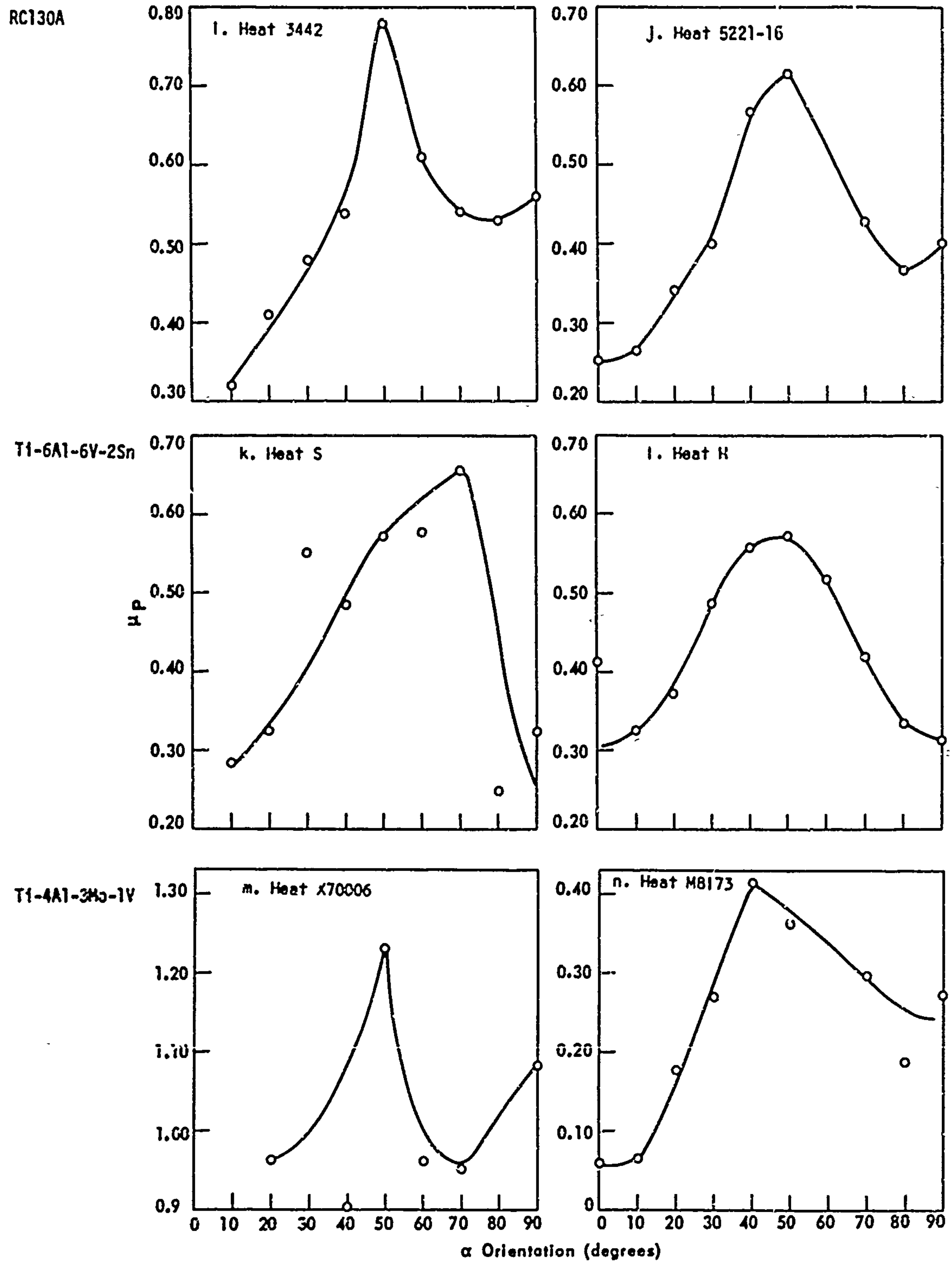


Figure 10i-n. VARIATION OF POISSON'S RATIO IN THE PLASTIC ZONE (μ_p) WITH SPECIMEN ORIENTATION (α)

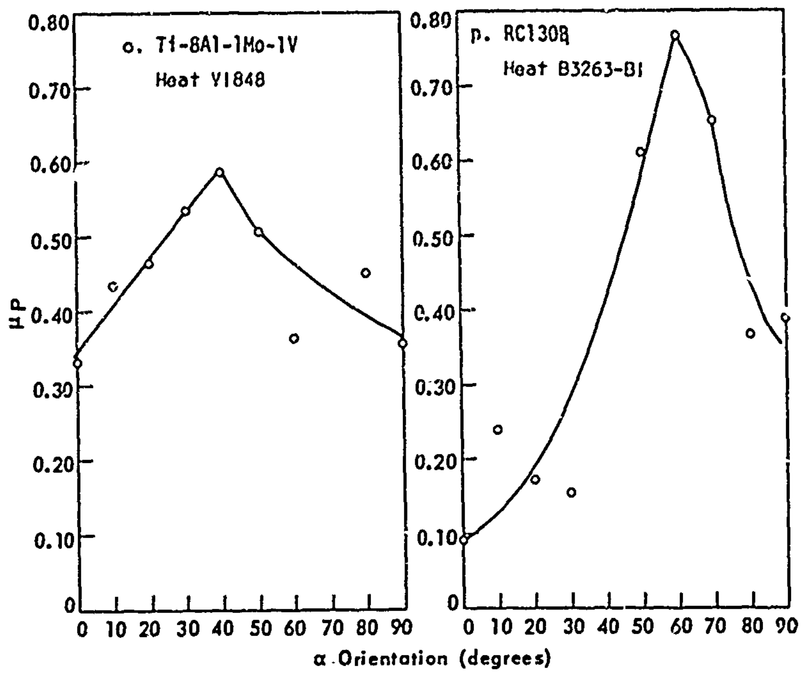


Figure 10o-p. VARIATION OF POISSON'S RATIO IN THE PLASTIC ZONE (μ_p) WITH SPECIMEN ORIENTATION (α)

higher than that for the rolling direction. It seems the alpha-deformation type texture produces the largest spread in values when the basal poles are tilted furthest toward the transverse direction.

Elongation

The percent elongation was not determined on all sheets and the information available is illustrated in Figure 11. It appears that relatively little can be said about the variation in percent elongation and its connection with texture. In some cases it seems there is a mild tendency for the elongation to peak at an angle of about 45 degrees.

SUMMARY

From this extensive program and previous work, it is now clearly established that titanium and titanium alloys can be anisotropic with respect to their uniaxial tensile properties. The most sensitive measure of this anisotropy appears to be the strain although the other mechanical properties such as Young's modulus, yield strength, and tensile strength are also influenced. This study has shown the general behavior patterns observed in commercially obtainable textures of several types. The patterns of behavior observed can be described in a qualitative way and further work is needed to

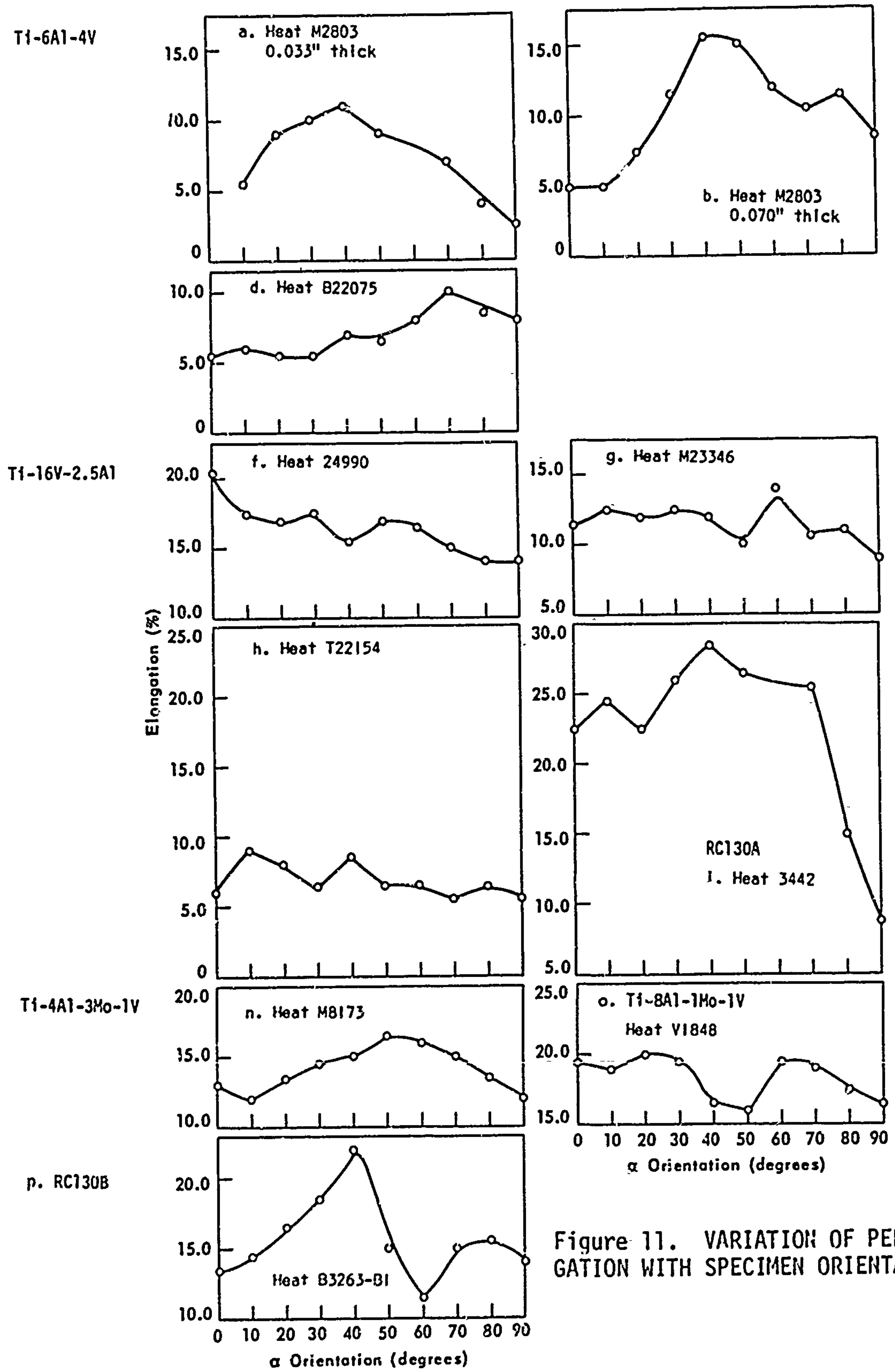


Figure 11. VARIATION OF PERCENT ELONGATION WITH SPECIMEN ORIENTATION (α)

more fully develop a quantitative understanding of the interrelationships between textured and mechanical properties of sheet materials.

It is hoped that the data presented here will serve to stimulate further inquiries into textured materials and encourage utilization in special structural applications where the improvements obtainable are at a premium. Further effort needs to be expended into discovering heat treatment and deformations necessary to obtain desirable textures. Once these textures can be controlled and are understood, it is possible that tremendous potential for improved mechanical properties will be realized.

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13. ABSTRACT

A study was carried out on the effect of specimen orientation on the sheet tensile properties of several titanium alloys. For these alloys, chemical analysis, microstructure, X-ray pole figures, and sheet tensile properties were determined at 10-degree increments from the rolling to the transverse direction. In addition to the conventional yield strength, tensile strength, and elongation values, strain gages were used to determine Young's modulus and Poisson's ratio. A study of plastic anisotropy was also made.

It is shown that several types of textures exist in these alloys and the characteristics of the mechanical properties are anisotropic and related to the texture type. A simple approximation of the anisotropic behavior patterns can be understood by relating these patterns to single-crystal properties. (Authors)

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